Front-door Concentrations and Personal Exposures of Danish Children to Nitrogen Dioxide

Ole Raaschou-Nielsen,[1,2] Henrik Skov,[3,4] Christian Lohse,[4,5] Birthe L. Thomsen,[1] and Jørgen H. Olsen[1,2]

[1]Division for Cancer Epidemiology, Danish Cancer Society, Copenhagen, Denmark; [2]Center for Biochemical and Occupational Epidemiology, The Danish Environmental Research Program, Århus, Denmark; [3]National Environmental Research Institute, Roskilde, Denmark; [4]Center for Air Pollution Processes and Models, The Danish Environmental Research Program, Århus, Denmark; [5]Department of Chemistry, University of Odense, Odense, Denmark

The aims of the study were to evaluate the front-door concentration of traffic exhaust fumes as a surrogate for the personal exposure of children and to study factors in the behavior and the environment of children that affect their personal exposure to nitrogen dioxide (NO_2). The exposure to NO_2 of 103 children living in Copenhagen and 101 children living in rural areas of Denmark was studied by measuring average concentrations over 1 week with diffusive badge samplers placed outside the front door of the home, inside the child's bedroom, and on each child. Detailed information about the activities of the children involving potential exposure to NO_2 was noted in diaries. The results indicated that the front-door concentration of traffic pollution might be used to classify the personal exposure of urban children, although misclassification would be introduced. Multiple regression analysis showed several factors that affected the personal NO_2 exposure of the children independently, including the front-door concentration, the bedroom concentration, time spent outdoors, gas appliances used at home, passive smoking, and burning candles. *Key words*: air pollution, children, exposure, nitrogen dioxide, traffic.
Envion Health Perspect 105:964–970 (1997). *http//ehis.niehs.nih.gov*

Many epidemiological studies deal with the effects of air pollution on children's health (*1–17*). Some have focused specifically on traffic exhaust fumes and used the residential outdoor concentration or the residential traffic density as surrogates for personal exposure (*15–17*).

The principal aim of this study was to determine if the front-door concentration of traffic exhaust fumes can be used to classify the actual personal exposure of children. Ideally, this requires measurements of a marker exclusively related to traffic exhaust fumes. Such a marker has not, to our knowledge, yet been identified. Thus, we used NO_2 as a marker of exposure to traffic exhaust fumes; the design of the study ensured that the contributions from sources other than traffic were reduced substantially. Moreover, the data allowed us to study factors in the environment and the behavior of Danish children that affect their exposure to NO_2.

Methods

Selection of children. Maps and traffic counts were used to identify 109 streets in central Copenhagen, Denmark, with or near to high traffic density and 215 streets in rural areas 20–50 km outside Copenhagen with low traffic density and no nearby major source of NO_2. We used the Central Population Registry, in which information including the sex, age, name, and residential address is registered for the entire Danish population, to identify all children between 4 and 12 years of age who lived on the 324 streets. A procedure to ensure geographical variation within the two residential areas was used, and the families of the children were chosen at random. The families received an invitation by mail to participate in the study, and a short questionnaire covering resident smokers, gas appliances in the kitchen, and potentially polluting heating sources such as coke ovens, woodburning stoves, and kerosene heaters. Participants were chosen on the basis of a low presence of these indoor sources of NO_2 in order to make the outdoor contribution dominant. Moreover, as Copenhagen is a city with few industries and a well-developed district heating system, traffic is the major source of outdoor NO_2 pollution (*18*). The rural areas are considered as reference in terms of traffic pollution.

NO_2 measurements. The measurements were carried out during 2 weeks in October 1994, 2 weeks in April 1995, 2 weeks in May 1995, and 1 week in June 1995. During each week, passive NO_2 samplers (badges) were placed in three locations each at approximately 15 urban dwellings and 15 rural dwellings: outside the front door, in the bedroom of the child, and on the child. The front-door badges were fixed under a cap of stainless steel. In the urban areas, they were typically placed 0.5 m from the fronts of the buildings, 4 m above street level, and within 10 m of the front door. In the rural areas, they were placed either on spears in gardens or 0.5 m from the fronts of the houses, 1.5 m above the ground, and within 10 m of the front door. In the bedrooms of the children, the samplers were placed 1–1.5 m above the floor and distant from the door, the window, and any source of heat. The children carried their personal badges outside their clothes, usually on a belt. When the children were bathing or doing sports, the badges were placed as close to them as possible; at night, the badges were placed beside the bed with the surface side up. Eight trained persons operating two by two started the measurements and gave the families careful instructions during one weekend and collected the badges the next weekend, sealed them and stored them in a freezer until analysis.

Diary notes. Each day the family filled in a printed diary covering the activities of the child; exact locations; time spent indoors, outdoors, in a car, in a bus, or in a tractor; time exposed to passive smoking; time when gas appliances were used in the kitchen at home; time spent near fire (for example burning candles, fireplaces, woodburning stoves, and barbecues); and time exposed to perceptible air pollution from point sources like factories. On the basis of the diary notes, we added the variable time spent in a city. For children in Copenhagen, a city was defined as within 10 km of the center of Copenhagen; for the rural children, suburbs of Copenhagen and towns with more than 20,000 inhabitants were also counted as cities. The variable time spent in a car or a bus was calculated as the sum of time spent in a car and time spent in a bus.

The families were instructed to report all occasions on which the child did not wear the personal badge, and in that case, to keep separate diaries for the child and the badge. Variables for activities noted in the diary were based on the diary of the badge to make sure that they corresponded to the personal measurement. If omissions or uncertainties were

Address correspondence to O. Raaschou-Nielsen, Division for Cancer Epidemiology, Danish Cancer Society, Strandboulevarden 49, DK-2100 Copenhagen Ø, Denmark.
The authors thank Ole Hertel, Ruwim Berkowicz, Åse Marie Hansen, Elisabetta Vignati, Steen Solvang Jensen, and Geert Schou for fruitful discussions and Visti Birk Larsen for assistance with data processing. Thanks are also due to the National Environmental Research Institute and the Agency of Environmental Protection, City of Copenhagen, who kindly provided monitoring data from chemiluminescence analyzers, and to all of the children and parents who participated in the study.
Received 28 February 1997, accepted 6 June 1997.

found in the returned diaries, we contacted the family within 1 week. Two people independently keyed in the information from the diaries, and a third person examined any differences. The time spent on each activity was calculated as the percent of the observation time, which was equal to the duration of the exposure of the child's badge.

Laboratory analysis. NO_2 was collected on the badges with triethanolamine as the substrate, which absorbs nearly 100% NO_2 and converts it to nitrite (*19*). The nitrite was analyzed on a segmented flow analyzer using Saltzman's reagents (*20*), followed by spectrophotometric detection at 540 nm. The amount of nitrite on the badges was converted to a mixing ratio by the constant of Yanagisawa and Nishimura (*19*). In each analytical run, two seven-points standard curves were used to determine the amount of nitrite. Furthermore, two series of four control standards were analyzed to ensure that the analytical run had proceeded properly. All control standards were prepared independently in the laboratory. At least three unexposed badges from each production series were analyzed, and the average was used as the zero-point. The detection limit for a 1-week average was 0.4 ppb NO_2.

Annual international intercalibration showed that the uncertainty of the analysis of nitrite standards was within 5% (*21*). On the basis of six pairs of field replicants, the coefficient of variation (standard deviation divided by mean) was estimated to be 4%; intercomparison with a TECAN chemiluminescence instrument (TECAN CLD 770 AL ppt; TECAN AG, Hombrechtikom, Switzerland), equipped with a photolytic NO_2 converter and placed in a rural area with little pollution, showed differences within 10%. In accordance with these results, the accuracy of the method has been estimated to be within 20% (*19*). We also tested the badge method against two chemiluminescence NO_x analyzers with molybdenum converters in urban areas. All analyzers were calibrated with certified permeation tubes of NO_2. When the badges were placed at the air intake of the monitoring stations, they showed significantly lower concentrations than the chemiluminescence analyzers (Table 1). The difference was expected, because several minor NO_y compounds such as peroxyacyl nitrate and HNO_3 are measured as NO_2 in the NO_x analyzers.

Table 1. Comparison of simultaneous 1-week NO_2 measurements (ppb) at the same location performed by a chemiluminescence NO_x analyzer and by the badge method

Measurement			
Analyzer	Badge	Ratio[a]	Difference[b]
12.8[c]	11.3	0.88	1.5
16.9[d]	13.0	0.77	3.9
25.3[d]	22.3	0.88	3.0
28.3[d]	25.1	0.89	3.2
31.0[d]	26.3	0.85	4.7
32.1[d]	27.5	0.86	4.6

[a]Significantly different from 1 (p = 0.0008); t-test of log(ratio) = 0.
[b]Significantly different from 0 (p = 0.0008) in t-test.
[c]Køge monitoring station.
[d]Jagtvej monitoring station.

Statistical methods. The relationship between the personal measurements (outcome variable) and the front-door measurements (explanatory variable) was analyzed in univariate linear regression analyses. Each residential region was analyzed separately. The analyses were based on the GLM procedure of SAS (SAS Institute, Cary, NC) (*22*).

The relationships between the personal measurements and the explanatory variables sex, age, traffic density at the address, NO_2 in the bedroom, NO_2 at the front door, and all variables from the diary were analyzed by multiple regression analysis (*23*). Multiple regression analysis was used to identify factors that influence the personal exposure of children, after correction for the other factors. The analysis was based on a mixed linear model with a region-dependent variance (the MIXED procedure of SAS) (*24*), as the residual variation was much larger among the children in Copenhagen than among the children in the rural areas. In the multiple analysis, the variables being outdoors, being in a city, riding in a car, riding in a bus, and riding in a car or a bus, were allowed to interact with residential region. We reduced the multiple model by successive exclusion of insignificant variables.

All tests in the multiple model were based on the likelihood ratio test statistic and those in the univariate analysis on the t-test statistic. p-Values refer to tests of no association between the explanatory variable(s) and the outcome variable.

Results

Participants and summary statistics. Of the 1,730 families invited to participate in the study, 204 were included (Table 2). Seven of the remaining 204 children were excluded because of missing values for outcome variables (exposure of the personal badge), loss of the badge (n = 3), destruction of the badge in a laundry machine (n = 1), not wearing the badge at all (n = 1), and errors in laboratory analyses (n = 2). One further front-door badge was vandalized, one indoor measurement was excluded by the laboratory because of an unrealistically low value (lower than any blank value), and one diary was excluded because of insufficient quality. The 197 children with valid exposure measurements consisted of 56 boys and 42 girls in Copenhagen and 49 boys and 50 girls in the rural districts. In Copenhagen, the majority of the homes were apartments

Table 2. Distribution of subjects invited to participate in the study

Invited	1,730
Nonrespondents	1,181
Respondents	549
Excluded	345[a]
Participants	204

[a]Reasons for exclusion were homes with resident smokers (n = 233), gas appliances at home (n = 56), heating sources like wood-burning stoves and kerosene heaters (n = 9), and reasons unrelated to the NO_2 measurements (n = 47) such as change of residence, inability to participate, and late response.

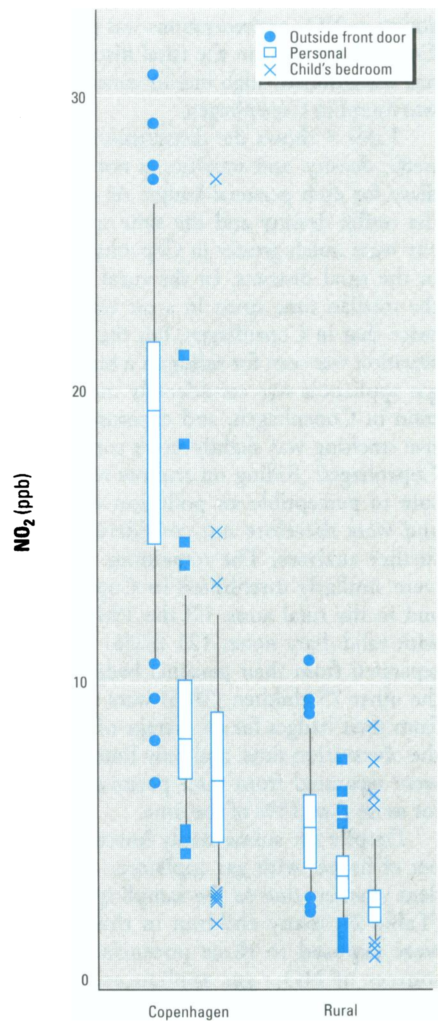

Figure 1. Box-and-whisker plots of 195 sets of NO_2 measurements in Copenhagen and rural districts. Each set includes one measurement outside the front door, one personal measurement, and one measurement in the bedroom of the child. The box encloses the middle half of the data, and a horizontal line bisects the box at the median. The lower whisker ends at the 5th percentile and the upper whisker at the 95th percentile. Values beyond these percentiles are shown separately.

in old four- to six-story buildings, but new apartments and one-family houses were also represented. Most of the families in the rural areas lived in one-family houses with gardens.

Figure 1 shows the levels and distributions of the NO_2 measurements as box-and-whisker plots. The front-door concentrations, indoor concentrations, and personal measurements were substantially higher in Copenhagen than in the rural districts. Moreover, Figure 1 shows a decreasing trend in the NO_2 concentrations from front-door measurements through personal measurements to the bedroom measurements both in Copenhagen and in the rural areas. This trend was consistent throughout the 7 weeks during which measurements were performed (data not shown). The variability in NO_2 concentrations was greater in Copenhagen than in the rural districts, and one exceptionally high indoor concentration was found in Copenhagen.

Table 3 shows the distributions of age, traffic density, and activities as noted in the diary for each personal badge. As expected, the traffic density and the time spent in a city were much greater in Copenhagen than in the rural districts. In the rural districts, the median time spent in a car was almost twice that in Copenhagen, but the opposite situation was seen for riding in a bus. Use of gas appliances was considerably more common in Copenhagen, and exposure to passive smoking was slightly more common in Copenhagen. Riding on tractors and exposure to perceptible air pollution were rare and were therefore not considered in the further analyses. The remaining variables were similarly distributed in Copenhagen and in the rural areas. Of the 196 children with valid diary notes, 121 (62%) were not separated from their personal badges at all; the other 75 children (38%) were separated from their badges for an average of 5.1% of the observation time, and only four children were separated from their personal badges for more than 15% of the time.

Despite the substantially lowered number of homes with gas appliances and resident smokers due to the sampling strategy (Table 2), many children in this sample were exposed to three potential indoor sources of NO_2: gas appliances, passive smoking, and fire (Table 3). For example, 10% of the children in Copenhagen were exposed to passive smoking for at least 8% of the observation time (2 hr/day).

Table 3. Distribution of age, traffic density, and activities

	Copenhagen children			Rural children		
	Median	10th percentile	90th percentile	Median	10th percentile	90th percentile
Age (years)	8.0	4.4	11.4	8.8	5.0	12.2
Traffic density (vehicles/day)	10,700	1000	19,800	75	10	400
Being outdoors[a]	10.8	5.9	21.5	12.4	5.1	25.2
Riding in a car[a]	0.7	0.0	2.3	1.6	0.6	3.4
Riding in a bus[a]	0.3	0.0	1.8	0.1	0.0	0.9
Riding on a tractor[a]	0.0	0.0	0.0	0.0	0.0	0.0
Riding in a car or bus[a]	1.2	0.0	3.3	2.0	0.6	3.9
Being in a city[a]	100.0	86.6	100.0	1.7	0.0	6.4
Passive smoking[a]	1.8	0.0	8.0	0.8	0.0	5.6
Gas appliances used at home[a]	0.0	0.0	3.1	0.0	0.0	0.0
Near fire[a]	0.8	0.0	6.3	1.2	0.0	4.4
Perceptible air pollution[a]	0.0	0.0	0.0	0.0	0.0	0.0

[a]Time spent on the activity in percent of observation time.

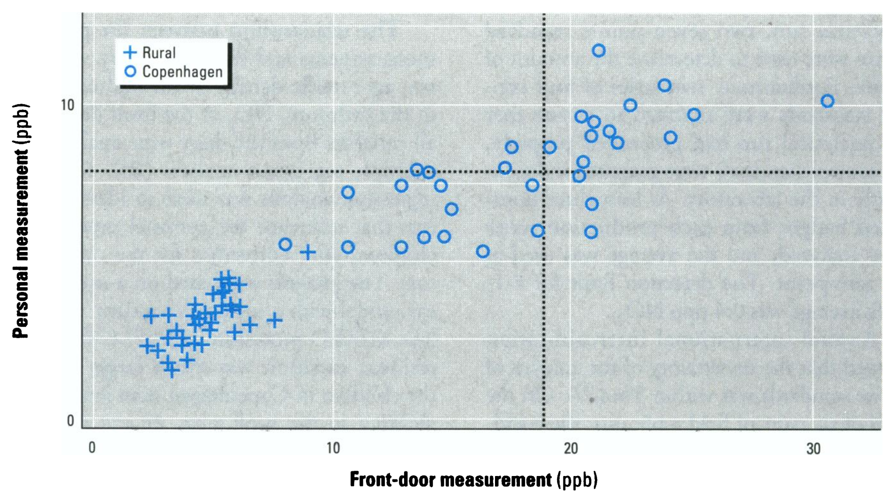

Figure 2. Plot of personal NO_2 measurements against NO_2 measurements at the front door in rural districts (n = 46) and in Copenhagen (n = 32). The median values for urban children are indicated by dotted lines.

Relationship between front-door concentration and personal exposure. First, the relationship was analyzed in the full sample of children. Linear regression analyses showed highly significant relationships between the two variables (p<0.0001 in both residential regions). The front-door concentrations accounted for 15 and 35% (r^2 values) of the variation in personal exposures in Copenhagen (n = 97) and in the rural districts (n = 99), respectively.

The presence of potential indoor sources of NO_2 in the full sample of children invalidated the assumption that NO_2 was a marker only of traffic exhaust fumes. Therefore, we considered a subset of children who reported exposure to gas appliances, passive smoking, and fire in the diary for less than 2% of the observation time. On the basis of this sample, the r^2 values were 49% for Copenhagen (n = 32) and 45% for the rural districts (n = 46). Figure 2 shows a plot of the front-door concentration against the personal exposure for this subset of children.

When the sample of children was further restricted by excluding those who reported exposure to either gas appliances or passive smoking for more than 1% or to fire for more than 2% of the observation time, the r^2 values were 59% in Copenhagen (n = 24) and 46% in the rural districts (n = 42).

We used the data shown in Figure 2 as an example of the potential epidemiological use of front-door concentrations of traffic exhaust fumes for classifying children into two exposure groups. Children whose front-door concentrations were below the median were classified as having low exposure and the other half of the children were classified as highly exposed. The actual exposure status was obtained from personal exposure measurements; children whose personal exposures were below the median were considered actually to have low exposure and the other half of the children actually to be highly exposed. Both the sensitivity (the proportion of correctly classified highly exposed) and the specificity (the proportion of correctly classified low exposure) of this classification method were 81% in Copenhagen and 74% in rural districts.

Multiple analysis. The multiple regression analysis was based on 194 observations without missing values, and the initial model included 13 explanatory variables and four interaction terms. First, we

Table 4. Multiple regression model of effects of explanatory variables on exposure of children's badges to NO_2 (n = 194)

Variable	Estimate[a]	Standard error	p-Value
Copenhagen			
(compared with rural districts)	0.1	1.1	0.93
Girl (compared with boys)	0.267	0.099	0.008
Age (year)	0.056	0.019	0.005
NO_2 in the bedroom (ppb)	0.440	0.037	<0.0001
NO_2 at the front door (ppb)	0.162	0.025	<0.0001
Being outdoors[b]	0.0242	0.0070	0.001
Passive smoking[b]	0.056	0.017	0.001
Gas appliances used at home[b]	0.202	0.091	0.03
Near fire[b]	0.052	0.026	0.05
Being in a city[b]	0.015	0.011	0.19
Riding in a car or bus[b]			
Rural districts	0.171	0.037	c
Copenhagen	-0.18	0.14	c

[a]Values given as ppb per unit of the variable. For dichotomous variables, the estimate is the difference; for example, the exposure of girls is estimated to be 0.267 ppb higher than that of boys.
[b]Time spent on the activity in percent of observation time.
[c]The p-value for the interaction between region and riding in a car or bus was 0.01.

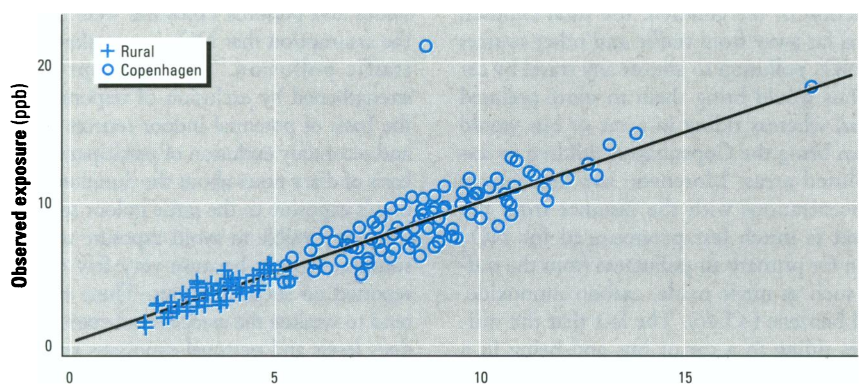

Figure 3. Plot of observed personal NO_2 exposure against NO_2 exposure predicted by the multiple regression model in rural districts and in Copenhagen (n = 194). The 1:1 line is shown on the figure.

removed two clearly insignificant interaction terms, residential region × time spent outdoors and residential region × time spent in a city (p = 0.53) and traffic density (p = 0.57). As the estimates for the variables time spent in a car and time spent in a bus were of the same magnitude, namely 0.188 and 0.112, respectively, in rural areas and -0.184 and -0.156, respectively, in Copenhagen, they were merged in the variable time spent in a car or a bus (p = 0.71). The final model had 11 explanatory variables and one interaction term (Table 4).

The model revealed that the effect of the bedroom concentration of NO_2 was about three times greater than the effect of the front-door concentration (0.440 compared with 0.162) and that the effect of use of gas appliances at home was several times greater than that of other indoor sources of NO_2, such as passive smoking and fire.

When the variable time spent in a car or a bus and the interaction term were tentatively removed from the final model, the effect of time spent in urban areas more than doubled and became significant (p = 0.008). Alternatively, if time spent in urban areas was removed, the effect of time spent in a car or a bus increased and the p-value correspondingly decreased. The two variables thus appeared to be partially competitive. When traffic density was added to the final model, the estimate and p-value for NO_2 at the front door did not change much, and when NO_2 at the front door was replaced by traffic density, the effect of traffic density was still insignificant (p = 0.08). Thus, traffic density was a poor surrogate for front-door NO_2 concentration. When gas appliances used at home was removed from the final model, the estimate and p-value for NO_2 in the bedroom did not change much; however, removing NO_2 in the bedroom from the model increased the estimate for gas appliances used at home from 0.202 to 0.513 and decreased the p-value from 0.03 to <0.0001. Most of the effect of gas appliances used at home appeared to be mediated through NO_2 in the bedroom. The combined variable being near fire included many indoor and outdoor activities, but burning candles indoors was the dominant subcategory, with regard both to the number of children exposed and the duration of exposure. Burning candles indoors could thus replace being near fire. When both variables were included simultaneously, neither was significant, while exclusion of one increased the significance of the remaining variable (p = 0.05 for both).

One observation corresponded to an extreme outlier, with a residual of 12.5 ppb (the second highest residual was 2.3 ppb). Exclusion of this outlier decreased the estimate for NO_2 at the front door from 0.162 to 0.130 and increased the estimate for NO_2 in the bedroom from 0.440 to 0.482, but all other estimates changed by less than one standard error. The p-values generally decreased, and being in a city became significant (p = 0.05). Figure 3 shows a plot of observed personal NO_2 exposure against the exposures predicted by the multiple model. Apart from the outlier, the model predicted the observed NO_2 exposures quite well.

Discussion

Epidemiological use of front-door concentration for exposure classification. The ideal method for exposure assessment in air pollution epidemiology is measurement on each participant, but in many cases this is not feasible. For example, epidemiological studies of cancer are usually designed as either very large (many thousand participants) prospective cohort studies or retrospective case–control studies. In the first case, the size of the study and the exposure period (usually many years) make it impossible to measure the personal exposure of each individual. In the second case, the retrospective character of the design is the limiting factor; it is impossible to measure exposures in the past. Thus, in many situations it is necessary to apply alternative exposure assessment methods.

In this study we focused on traffic exhaust fumes, which dominate outdoor air pollution in Danish cities. Newly developed dispersion models (*25*) claim to predict outdoor concentrations in streets if information about traffic density, street width, and building configuration is available. In Denmark, this information is also available historically; therefore, dispersion models might be useful in the exposure assessment if the front-door concentration of traffic exhaust can be used to classify the personal exposure of individuals living at the location.

In a subset of the children in this study with limited exposure to indoor sources, the front-door concentrations accounted for 49% of the variation in personal exposures in Copenhagen and 45% in rural areas. As an example of the use of front-door concentrations for exposure classification, we found the sensitivity and the specificity to be 81% for children in Copenhagen and 74% in rural districts. It is obvious that use of this classification method would lead to misclassification of the exposure status of children and that the misclassification (given that it is nondifferential) would lead to underestimation of the true relative risk (*26,27*). Nevertheless, sensitivities and specificities for classification methods of about 80% are probably not exceptions in epidemiological research.

Factors related independently to exposure to NO_2. The multiple analysis showed that the NO_2 concentrations in the bedroom and at the front door significantly affected the NO_2 exposure of Danish children, which is consistent with findings in previous studies of personal NO_2 exposure (*28–33*). The effect of being outdoors and in a city was also not a surprise, as substantially higher concentrations were present outdoors than indoors and in Copenhagen in comparison with rural districts.

Gas appliances have repeatedly been identified as an important source of personal NO_2 exposure (*28,29,32–38*). We found an effect of only borderline significance, probably due to several causes. First, most of the effect of gas appliances was included via the effect of the NO_2 concentration in the bedroom; removing the bedroom concentration from the regression model decreased the *p*-value for gas appliances to <0.0001. Second, the highest NO_2 concentrations have been reported from gas stoves with continuously burning pilot lights (*28,39,40*), which are rarely used in Denmark. Third, in contrast to most previous studies, we dealt only with children who might be expected to be less exposed than adults because 1) NO_2 concentrations in the kitchens and living rooms of houses with gas stoves decrease with decreasing height (*41*) and 2) children spend less of the time than their mothers do in the kitchen (*36*). Fourth, in the diary we asked about use of gas appliances at home, not near the child, which would tend to dilute the effect on the personal badge. Finally, the selection of the participants reduced the number of homes with gas appliances.

In the present study, we found that exposure to passive smoking increased the NO_2 exposure of children. Passive smoking has not previously been reported to increase personal NO_2 exposure, but the finding seems reliable because several studies have shown that smoking increases indoor NO_2 concentrations (*39,42–44*).

We found a significant effect of being near fire and particularly near burning candles. Candles are frequently used in Denmark, on the dinner table, at social gatherings like birthdays, or just to feel comfortable. In this sample, 10% of the children were exposed for more than about 1 hr/day. To our knowledge, the association between burning candles and NO_2 concentrations has not been studied previously, but an effect of burning candles seems likely due to formation of NO_2 during the combustion process.

We expected that riding in cars and buses would increase the exposure of children to NO_2, as we assumed that elevated levels on the streets would be reflected inside vehicles. Riding in cars and buses increased the exposure of rural children but decreased that of Copenhagen children. We believe that the observed effects are related to the selection of the children: the rural children lived far away from traffic and other sources of NO_2 pollution so almost any travel by car or bus would bring them to more polluted areas, whereas riding in a car or bus would often bring the Copenhagen children to less polluted areas. Moreover, the decrease of concentrations with the distance from the street is much less pronounced for NO_2 than for primary air pollutants from the traffic such as nitric oxide, carbon monoxide, and benzene (*45,46*). The fact that the variables riding in a car or bus and being in a city in the multiple model were at least partly competitive supports this point of view.

The results indicated that older children and girls experienced higher NO_2 exposure. If these findings are not artefacts, they must be related to some behavior of the children that was not included in the multiple model. One explanation for the effect of age and being a girl could be that older children and girls are often more conscientious than younger children and boys and might therefore have followed the instructions about wearing the badge outside the clothes more accurately, thus increasing the measured concentration. This explanation is speculative, however, and we consider the results as chance findings until confirmed in future studies.

Validity of findings. Field replicants and comparisons with other measurement methods indicated acceptably low uncertainty of the badge measurement method, and the diary notes indicated that the children and families followed the instructions. Therefore, we believe that the measurements reflect the actual NO_2 concentrations.

A Danish study showed small systematic seasonal changes in street concentrations of NO_2 (*47*) and any overestimation or underestimation of front-door levels due to random variation is probably small because we measured during 7 different weeks. Moreover, as the outdoor levels found in Copenhagen were similar to those found at a number of other locations, including Toronto, Canada (*30*), Watertown, Massachusetts (*34*), Veenendal, Holland (*36*), and Middlesbrough, United Kingdom (*48*), we believe that the outdoor levels found in Copenhagen are representative of those in many urban locations. The outdoor levels found in rural districts are probably representative of those in areas with no major local sources of NO_2 pollution. The selection of participants, which reduced the number of children living in homes with resident smokers and gas appliances, certainly reduced the average indoor and personal exposures with respect to those in random samples in similar residential areas.

The results for a relationship between front-door concentrations of traffic exhaust fumes and personal exposures were based on the assumption that NO_2 is a marker only of traffic pollution. This assumption was strengthened by exclusion of respondents on the basis of potential indoor sources of NO_2 and secondary exclusion of participants on the basis of diary notes about the duration of children's exposure to the same indoor sources. It was not possible to avoid exposure to indoor sources entirely because very few children reported no such exposures. These exposures tend to weaken the association between front-door levels and personal exposures and, compared to the ideal situation with no indoor sources, we would expect the results of this study to be underestimates of the association. In Copenhagen, it is reasonable to consider NO_2 at the front door as a marker of traffic pollution because traffic is the dominant source of NO_2 in the streets. That is not the case in the rural districts, where the results cannot be assigned to any specific local source of outdoor NO_2 pollution.

The multiple regression analysis was based on the full sample of children. The low proportion of children exposed to indoor sources would tend to diminish the possibility of significant results for those indoor sources, but it would not discredit the significant findings. The estimates derived from a regression analysis are valid only within the range of the explanatory variables. The full sample of children did include homes with indoor sources of NO_2, and the exposure to indoor sources of the children living in those homes were probably similar to the exposure of other children with the same indoor sources. Thus, the ranges of the explanatory variables in the multiple analysis were probably similar to those in a random sample (though the averages would be higher in a random sample), and the results can probably be generalized without restrictions related to the sample strategy.

Our study showed a highly significant relationship between front-door concentration and personal exposure to NO_2 in a selected sample of Danish children. In the context of epidemiological studies of traffic pollution, the results indicate that the front-door concentration might be used to classify the personal exposure of urban children, although it would imply misclassification that cannot be ignored. Any major benefit of this classification method would depend on reliable dispersion models that can substitute for measurements at the front door. In most rural areas, the method would be irrelevant because of the negligible traffic density. Moreover, the study shows that passive smoking and the burning of candles increase personal exposure to NO_2, which, to our knowledge, has not been reported previously. Finally, the study confirms that indoor levels and use of gas appliances affect personal exposure to NO_2.

References

1. Buchdahl R, Parker A, Stebbings T, Babiker A. Association between air pollution and acute childhood wheezy episodes: prospective observational study. Br Med J 312:661–665 (1996).
2. Neas LM, Dockery DW, Koutrakis P, Tollerud DJ, Speizer FE. The association of ambient air pollution with twice daily peak expiratory flow rate measurements in children. Am J Epidemiol 141:111–122 (1995).
3. Søyseth V, Kongerud J, Haarr D, Strand O, Bolle R, Boe J. Relation of exposure to airway irritants in infancy to prevalence of bronchial hyper-responsiveness in schoolchildren. Lancet 345:217–220 (1995).
4. Hoek G, Brunekreef B, Kosterink P, Van Den Berg R, Hofschreuder P. Effect of ambient ozone on peak expiratory flow of exercising children in the Netherlands. Arch Environ Health 48:27–32 (1993).
5. Krzyzanowski M, Quackenboss JJ, Lebowitz MD. Relation of peak expiratory flow rates and symptoms to ambient ozone. Arch Environ Health 47:107–115 (1992).
6. Spektor DM, Hofmeister VA, Artaxo P, Brague JAP, Echelar F, Nogueira DP, Hayes C, Thurston GD, Lippmann M. Effects of heavy industrial pollution on respiratory function in the children of Cubatao, Brazil: a preliminary report. Environ Health Perspect 94:51–54 (1991).
7. Islam MS, Schlipköter H-W. Reversible fraction of airway resistance in healthy children of areas with different levels of atmospheric pollutants. Exp Pathol 37:23–26 (1989).
8. Goren AI, Hellmann S. Prevalence of respiratory symptoms and diseases in schoolchildren living in a polluted and in a low polluted area in Israel. Environ Res 45:28–37 (1988).
9. Ware JH, Ferris BG Jr, Dockery DW, Spengler JD, Stram DO, Speizer FE. Effects of ambient sulfur oxides and suspended particles on respiratory health of preadolescent children. Am Rev Respir Dis 133:834–842 (1986).
10. Neas LM, Dockery DW, Ware JH, Spengler JD, Speizer FE, Ferris BG Jr. Association of indoor nitrogen dioxide with respiratory symptoms and pulmonary function in children. Am J Epidemiol 134:204–219 (1991).
11. Rutishauser M, Ackermann U, Braun C, Gnehm HP, Wanner HU. Significant association between outdoor NO_2 and respiratory symptoms in preschool children. Lung (suppl):347–352 (1990).
12. Ogston SA, Florey CV, Walker CH. The Tayside infant morbidity and mortality study: effect on health of using gas for cooking. Br Med J 290:957–960 (1985).
13. Marbury MC, Maldonado G, Waller L. The indoor air and children's health study: methods and incidence rates. Epidemiology 7:166–174 (1996).
14. Neas LM, Dockery DW, Ware JH, Spengler JD, Ferris BG Jr, Speizer FE. Concentration of indoor particulate matter as a determinant of respiratory health in children. Am J Epidemiol 139:1088–1099 (1994).
15. Oosterlee A, Drijver M, Lebret E, Brunekreef B. Chronic respiratory symptoms in children and adults living along streets with high traffic density. Occup Environ Med 53:241–247 (1996).
16. Wjst M, Reitmeir P, Dold S, Wulff A, Nicolai T, Von Loeffelholz-Colberg EF, Von Mutius E. Road traffic and adverse effects on respiratory health in children. Br Med J 307:596–600 (1993).
17. Savitz DA, Feingold L. Association of childhood cancer with residential traffic density. Scand J Work Environ Health 15:360–363 (1989).
18. Larsen PB, Larsen JC, Fenger J, Jensen SS. Evaluation of Health Impacts of Air Pollution from Road Traffic [in Danish with a summary in English]. Environmental project no 352. Copenhagen:Danish Environmental Protection Agency, 1997.
19. Yanagisawa Y, Nishimura H. A badge-type personal sampler for measurement of personal exposure to NO_2 and NO in ambient air. Environ Int 8:235–242 (1982).
20. Gerboles M, Amantini L. Validation of Measurement by NO_2 Passive Sampler. A Comparison with Chemiluminescent Monitor. Technical Note TN I/93/107. Varese, Italy:Environmental Institute, Atmospheric Chemistry Unit, 1993.
21. Hanssen JE, Skjelmoen JE. The Fourteenth Intercomparison of Analytical Methods within EMEP. EMEP/CCC Report 3/95. Kjeller, Norway:Norwegian Institute for Air Research, 1995.
22. SAS Institute, Inc. SAS/STAT User's Guide, Release 6.03 Edition. Cary, NC:SAS Institute, Inc., 1988.
23. Altman D. Practical Statistics for Medical Research. 1st ed. London:Chapman & Hall, 1991.
24. SAS Institute, Inc. SAS/STAT Software Changes and Enhancements through Release 6.11. Cary, NC:SAS Institute, Inc., 1996.
25. Berkowicz R, Palmgren F, Hertel O, Vignati E. Using measurements of air pollution in streets for evaluation of urban air quality—meterological analysis and model calculations. Sci Total Environ 189/190:259–265 (1996).
26. Copeland KT, Checkoway H, McMichael AJ, Holbrook RH. Bias due to misclassification in the estimation of relative risk. Am J Epidmiol 105:488–495 (1977).
27. Flegal KM, Brownie C, Haas JD. The effects of exposure misclassification on estimates of relative risk. Am J Epidemiol 123:736–751 (1986).
28. Spengler J, Schwab M, Ryan PB, Colome S, Wilson AL, Billick I, Becker E. Personal exposure to nitrogen dioxide in the Los Angeles basin. J Air Waste Manage Assoc 44:39–47 (1994).
29. Quackenboss JJ, Spengler JD, Kanarek MS, Letz R, Duffy CP. Personal exposure to nitrogen dioxide: relationship to indoor/outdoor air quality and activity patterns. Environ Sci Technol 20:775–783 (1986).
30. Silverman F, Corey P, Mintz S, Olver P, Hosein R. A study of effects of ambient urban air pollution using personal samplers; a preliminary report. Environ Int 8:311–316 (1982).
31. Nitta H, Maeda K. Personal exposure monitoring to nitrogen dioxide. Environ Int 8:243–248 (1982).
32. Quackenboss JJ, Kanarek MS. Personal monitoring for nitrogen dioxide exposure: methodological considerations for a community study. Environ Int 8:249–258 (1982).
33. Dockery DW, Spengler JD, Reed MP, Ware J. Relationships among personal, indoor and outdoor NO_2 measurements. Environ Int 5:101–107 (1981).
34. Clausing P, Mak JK, Spengler JD, Lenz R. Personal NO_2 exposures of high school students. Environ Int 12:413–417 (1986).
35. Fischer P, Brunekreef B, Boleij JSM. Indoor NO_2 pollution and personal exposure to NO_2 in two areas with different outdoor NO_2 pollution. Environ Monit Assess 6:221–229 (1986).
36. Noy D, Brunekreef B, Boleij JSM, Houthuijs D, De Koning R. The assessment of personal exposure to nitrogen dioxide in epidemiological studies. Atmos Environ 24A:2903–2909 (1990).
37. Houthuijs D, Dijkstra L, Brunekreef B, Boleij JSM. Reproducibility of personal exposure estimates for nitrogen dioxide over a two year period. Atmos Environ 24A:435–437 (1990).
38. Harlos DP, Marbury M, Samet J, Spengler JD. Relating indoor NO_2 levels to infant personal exposures. Atmos Environ 21:369–376 (1987).
39. Goldstein BD, Melia RJ, Chinn S, Florey CV, Clark D, John HH. The relation between respiratory illness in primary schoolchildren and the use of gas for cooking—II. Factors affecting nitrogen dioxide levels in the home. Int J Epidemiol 8:339–345 (1979).
40. Marbury MC, Harlos DP, Samet JM, Spengler JD. Indoor residential NO_2 concentrations in Albuquerque, New Mexico. J Air Pollut Control Assoc 38:392–398 (1988).
41. Goldstein IF, Andrews LR, Hartel D. Assessment of human exposure to nitrogen dioxide, carbon monoxide and respirable particulates in New York inner-city residences. Atmos Environ 22:2127–2139 (1988).
42. Baker RR, Case PD, Warren ND. The build-up and decay of environmental tobacco smoke constituents as a function of room conditions. In: Indoor and Ambient Air Quality (Perry R, Kirk PW, eds). London:Selper Ltd, 1988;121–130.
43. Weber A, Fischer T. Passive smoking at work. Int Arch Occup Environ Health 47:209–221 (1980).
44. Good BW, Vilcins G, Harvey WR, Clabo DA Jr, Lewis AL. Effect of cigarette smoking on residential NO_2 levels. Environ Int 8:167–175 (1982).
45. Rodes CE, Holland DM. Variations of NO, NO_2 and O_3 concentrations downwind of a Los Angeles freeway. Atmos Environ 15:243–250 (1981).
46. Laxen DP, Jenson RA, Brooks K. Nitrogen

dioxide at the building facade in relation to distance from road traffic. In: Indoor and Ambient Air Quality (Perry R, Kirk PW, eds). London:Selper Ltd, 1988;40–45.

47. Kemp K, Palmgren F. Air pollution in Danish cities [in Danish with an English summary]. TEMA-rapport 1994/2. Roskilde, Denmark: National Environmental Research Institute, 1994.

48. Florey CV, Melia RJ, Chinn S, Goldstein BD, Brooks AG, John HH, Craighead IB, Webster X. The relation between respiratory illness in primary schoolchildren and the use of gas for cooking—III. Nitrogen dioxide, respiratory illness and lung infection. Int J Epidemiol 8:347–353 (1979).